Components in wireless technology, 5XTC0

Module 6
Lecture: Basics of Power Amplifiers and Mixers

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Where innovation starts

Outline

- RF specifications
  - Gain
  - Noise
    - Recap: thermal noise, noise figure, constant noise circles
  - Linearity
- Transceiver functions
- Basics of mixers
  - RX case
  - TX case
- Basics of power amplifiers

Learning Objectives

- Understand RF specifications
- Recap noise, noise figure and constant noise circles
- Be able to explain transceiver functions
- Understand operation of mixers in time and frequency domain for
  - RX case
  - TX case
- Understand principle of switching mixer
- Understand principle of power generation
- Be able to explain power amplifier classes

Literature

- Slides from this lecture have been based on books:
  - Behzad Razavi – RF Microelectronics
    - RF specifications – chapter 2
    - Mixers -> chapter 6
    - Power amplifiers -> chapter 12
  - Vojkan Vidojkovic – Adaptive Multistandard Front-ends
    - Image rejection, transceiver functions – chapter 2

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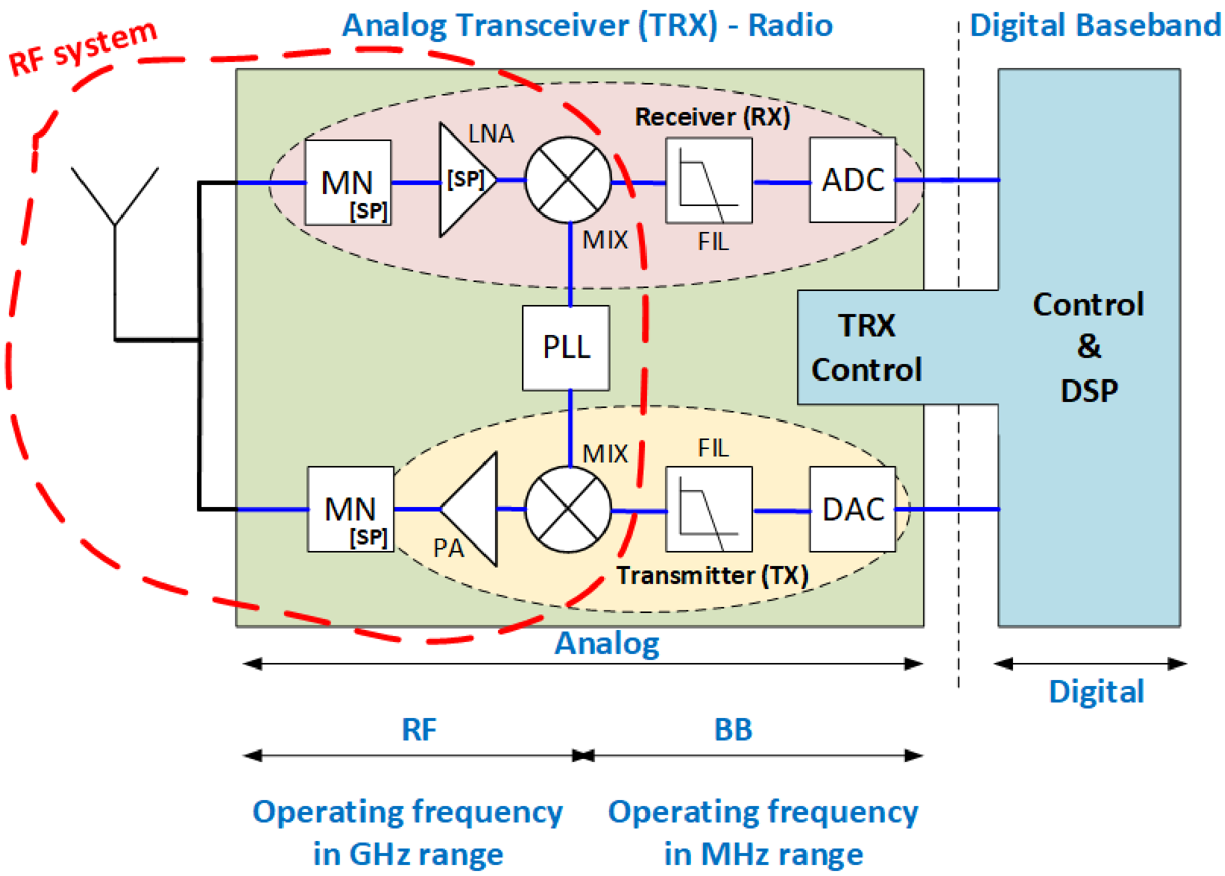
RF systems – transceiver block diagram



TRX functions

- Data conversion
- Filtering/selectivity
- Frequency conversion
- Amplification
- Frequency synthesis

Legend

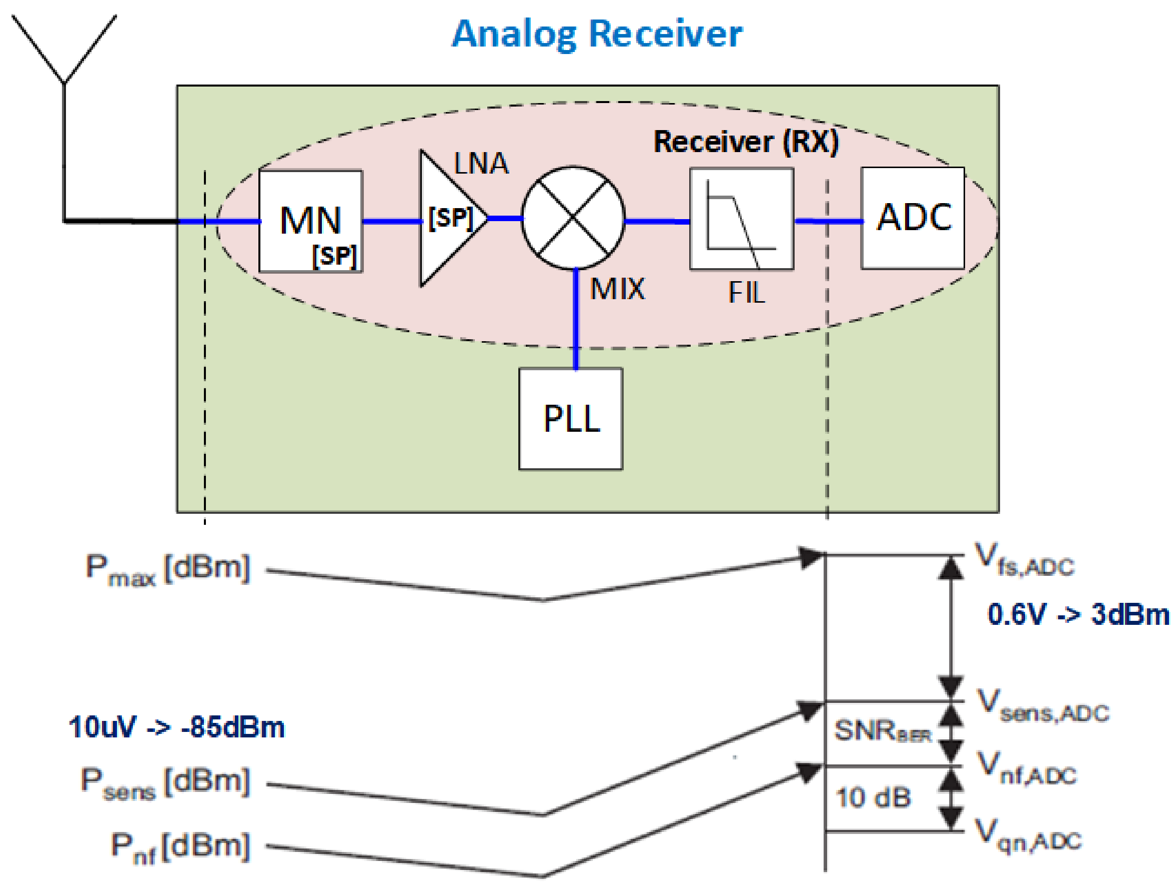
- RF – radio frequency
- BB - baseband
- MN – matching netwok
- LNA – low noise amplifier
- MIX – mixer
- FIL – filter
- PA – power amplifier
- ADC – analog to digital converter
- DAC – digital to analog converter
- DSP – digital signal processing
- PLL – phased locked loop

RF specifications

- Small signal
  - Gain
  - Noise figure (NF)
  - Input third-order intercept point
  - Input second order intercept point
- Large signal
  - 1-dB compression point

Linearity specifications

Why do we need gain?



- **Gain is required for signal conditioning**
- **Module 4 was dedicated to amplifier gain**

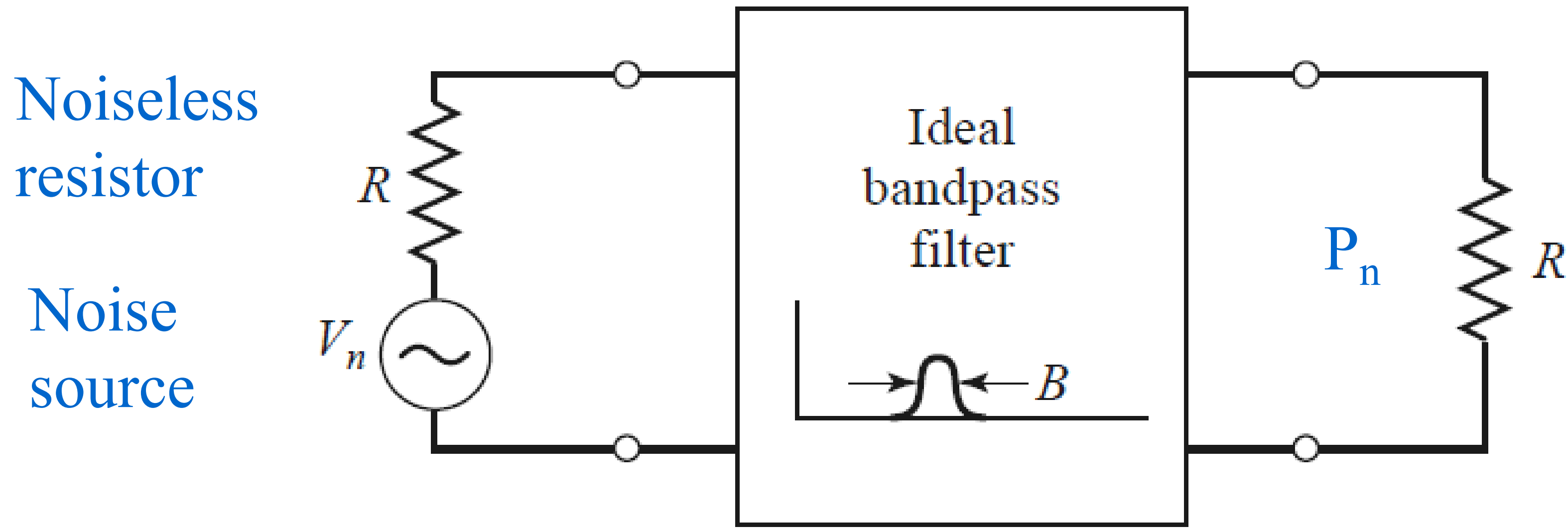
Why do we need to analyze noise?

- **Link budget allows to calculate received signal power S across a wireless link**
- **To transmit information across a wireless link, the received signal power must be significantly larger than the noise power N.**
- **The ratio between the signal power and the noise power is called "Signal-to-noise ratio" SNR:**

$$SNR = \frac{S}{N}$$

- **If we cannot distinguish the signal from the noise we cannot extract the information!**

White noise: Representation of a resistor as a noiseless resistor and a noise voltage source



Available noise power:

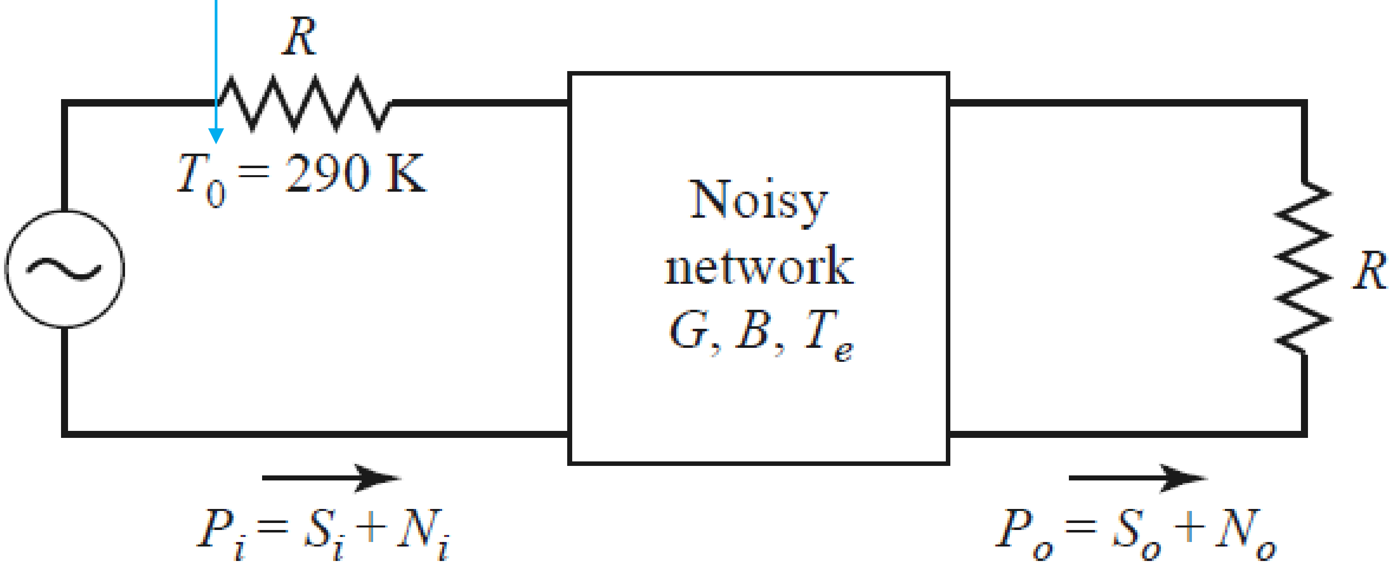
$$\boxed{P_n = \frac{V_N^2}{4R_N} = k_B T B}$$

What is the noise power at room temperature (300 K) for a bandwidth of 1Hz? Calculate it in W as well as in dBm.

$$k_B = 1{,}38 \cdot 10^{-23} \frac{kgm^2}{s^2 K} \qquad T(K) = T\left({}^oC\right) + 273$$

Definition: Noise figure

For room temperature input noise level!

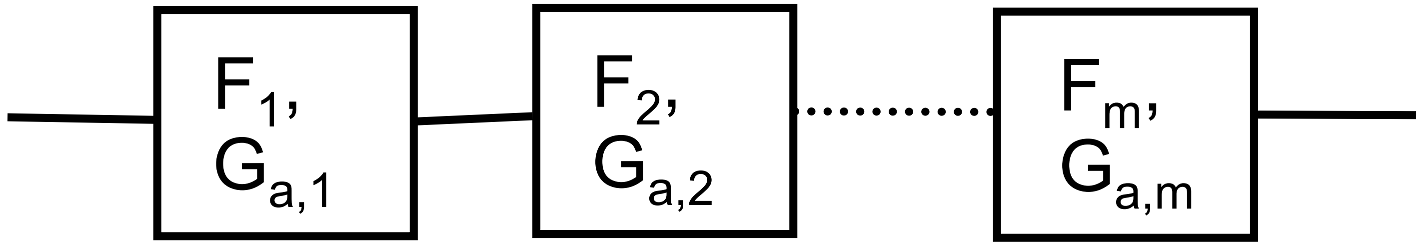


$$F = \frac{S_i / N_i}{S_o / N_o} = \frac{S_i}{S_o}\frac{N_o}{N_i} = \frac{1}{G}\frac{G k_B \left(T_0 + T_e\right) B}{k_B T_0 B} = 1 + \frac{T_e}{T_0} > 1$$

NF = *10 Log (F)*

- NF -> noise figure (dB)
- F -> noise factor

Cascaded NF: Friis' formula



System with cascaded sub-systems with noise figure F_m and available gain $G_{a,m}$

$$F_{total} = 1 + (F_1 - 1) + \frac{F_2 - 1}{G_{a,1}} + \ldots + \frac{F_m - 1}{G_{a,1} G_{a,2} \ldots G_{a,(m-1)}}$$

Noise figure of an amplifier (1)

- Noise figure of a 2-port amplifier:

$$F = F_{\min} + \frac{r_N}{g_S}\left|\underline{y}_S - \underline{y}_{opt}\right|^2$$

Normalized equivalent noise resistor: $r_n = \frac{R_n}{Z_0}$

Source admittance: $\underline{Y}_S = g_S + jb_S$

Minimum noise figure for the chosen bias point: $F_{\min} = \min(F)$

- Expression with the reflection coefficients Γ_S and Γ_{opt}

Scaling factor "sensitivity to offest"

$$F = F_{\min} + 4r_N \underbrace{\frac{\left|\underline{\Gamma}_S - \underline{\Gamma}_{opt}\right|^2}{\left(1-\left|\underline{\Gamma}_S\right|^2\right)\cdot\left|1+\underline{\Gamma}_{opt}\right|^2}}_{\text{Offset to optimum value}}$$

Constant noise circles

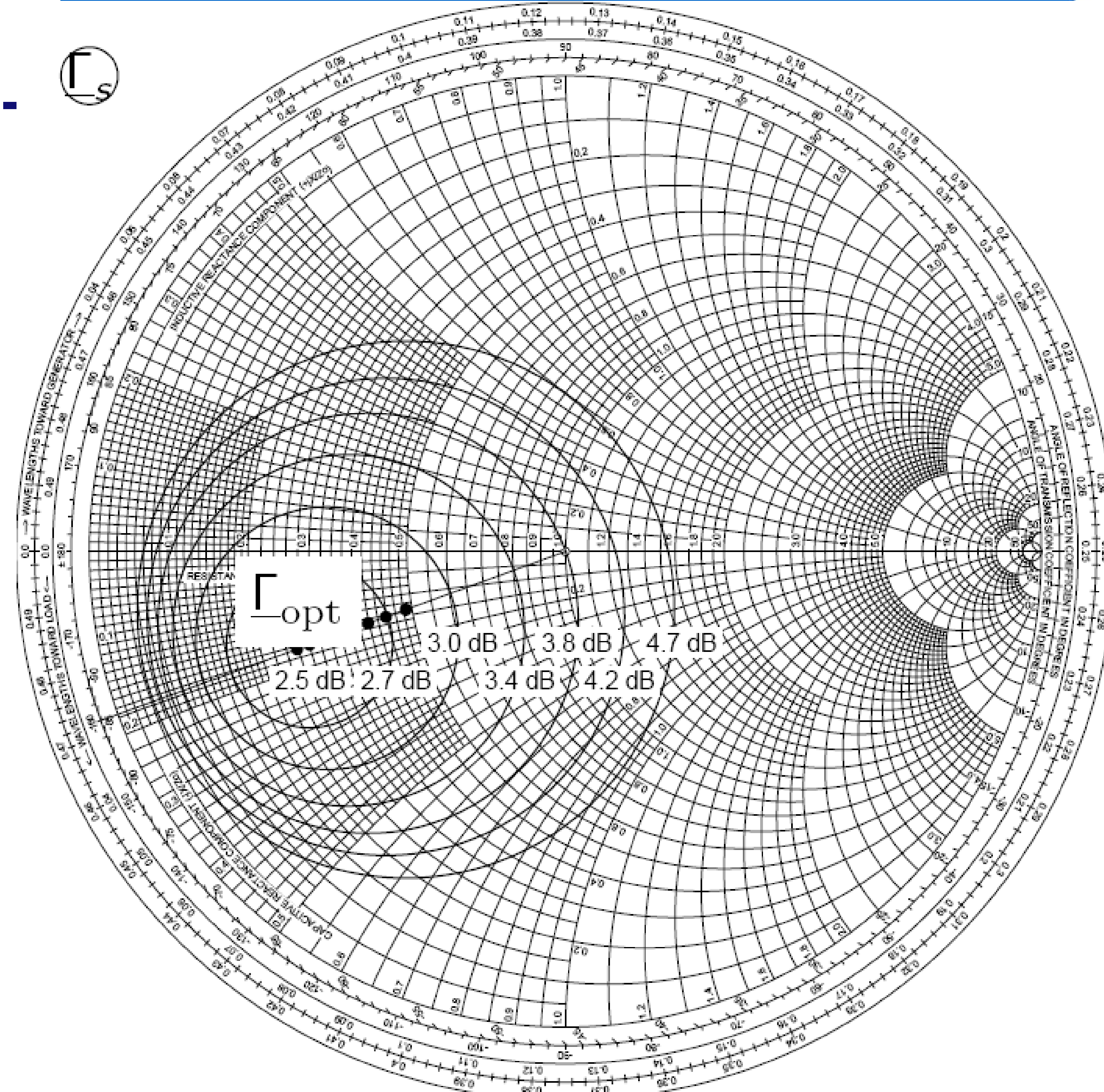
Centers: $\underline{C}_F = \dfrac{\Gamma_{opt}}{1+N}$

Radii: $R_F = \dfrac{1}{1+N}\sqrt{N^2 + N(1-\left|\Gamma_{opt}\right|^2)}$

With the "Noise figure parameter N" defined as:

$$\Delta F_n' = N = \left(F - F_{\min}\right)\frac{\left|1+\underline{\Gamma}_{opt}\right|^2}{4r_n} = \frac{\left|\underline{\Gamma}_S - \underline{\Gamma}_{opt}\right|^2}{1-\left|\underline{\Gamma}_S\right|^2}$$

Constant noise-circles in the source-reflection-coefficient Smith Chart



Design for specific noise figure

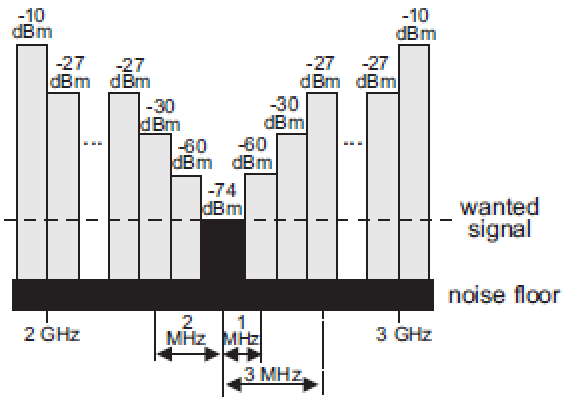
Typically the values of Γ_{opt}, r_n and F_{min} are known for the transistor.

The amplifier specification requires a noise figure F and a gain G.

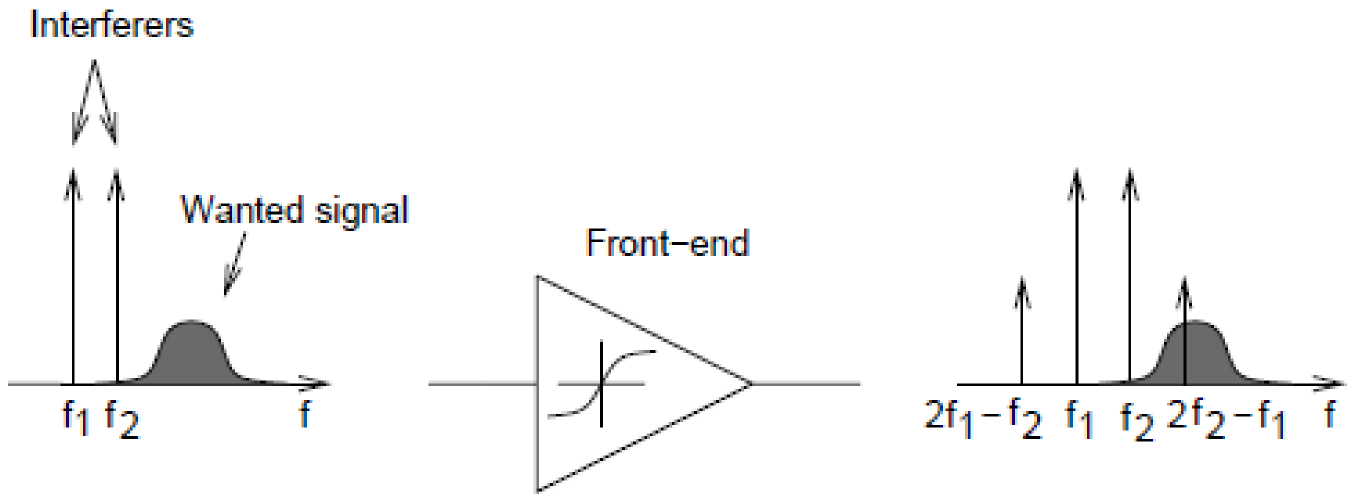
Procedure:

1. Calculate N
2. Calculate C_F and R_F
3. Draw the constant noise circle for the required F in the Smith chart as well as the input section constant gain circle for several G_S
4. Choose a value for Γ_S that is on the desired noise circle and a certain gain circle
5. The remaining gain must come from the transistor and the output matching stage

Why do we need to analyse linearity?



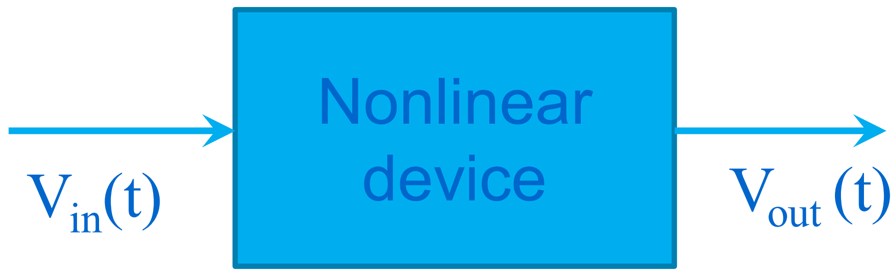
- Typical scenario in wireless communications
- Very weak wanted signal in vicinity of strong interferers



- SNR degradation due to nonlinearity

Effect of nonlinear devices on the signal

E.g. transistors, diodes

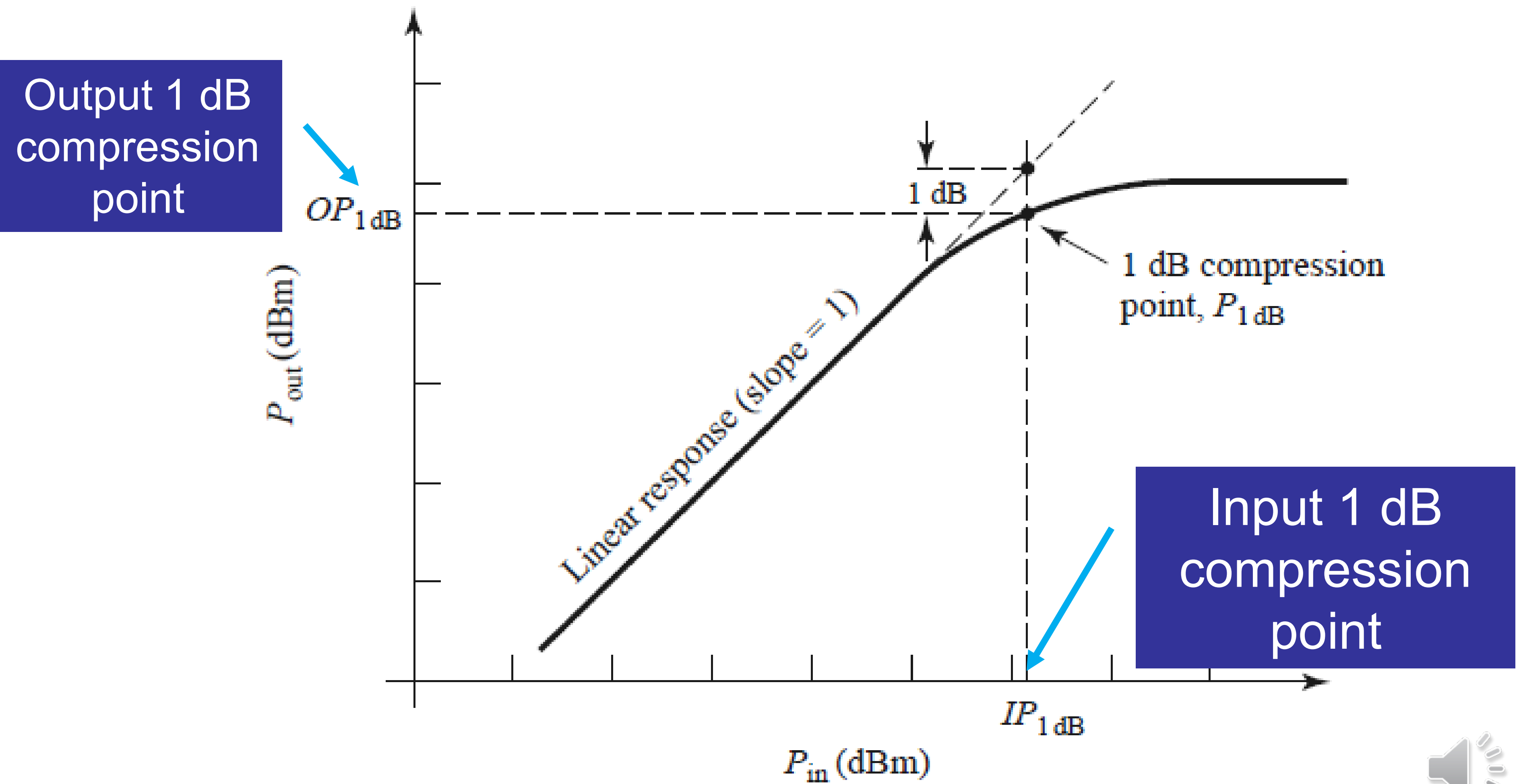


$$v_{out}(t) = v_{out,DC} + a_1 v_{in}(t) + a_2 v_{in}^2(t) + a_3 v_{in}^3(t) + \ldots$$

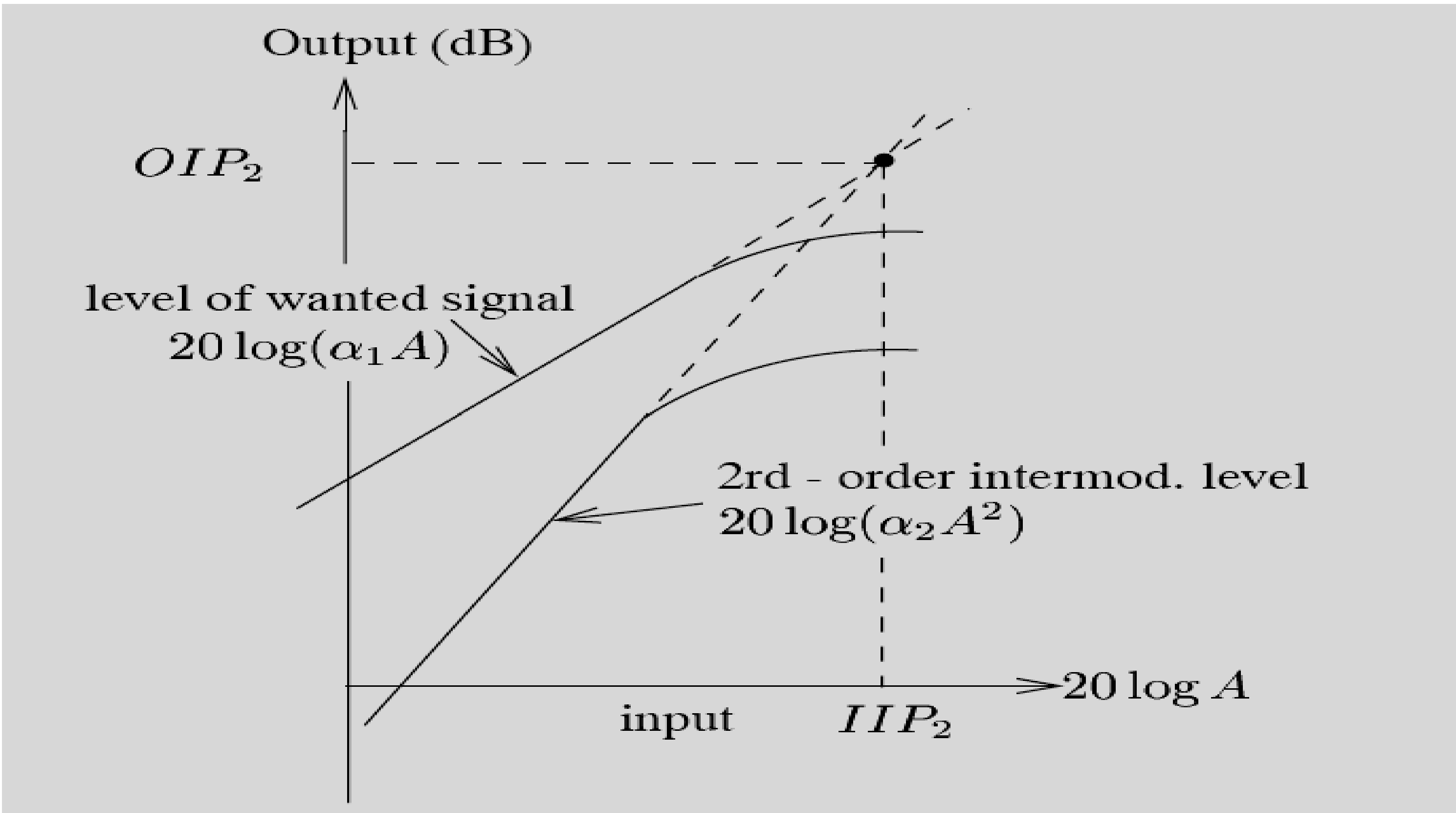
- Harmonic generation (multiples of a fundamental signal)
- Saturation (gain reduction in an amplifier)
- Intermodulation distortion (products of a two-tone input signal)
- Cross-modulation (modulation transfer from one signal to another)
- AM-PM conversion (amplitude variation causes phase shift)
- Spectral regrowth (intermodulation with many closely spaced signals)

More info: book from B. Razavi, RF Microelectronics, chapters 2.1.1 and 2.1.2

1 dB compression point

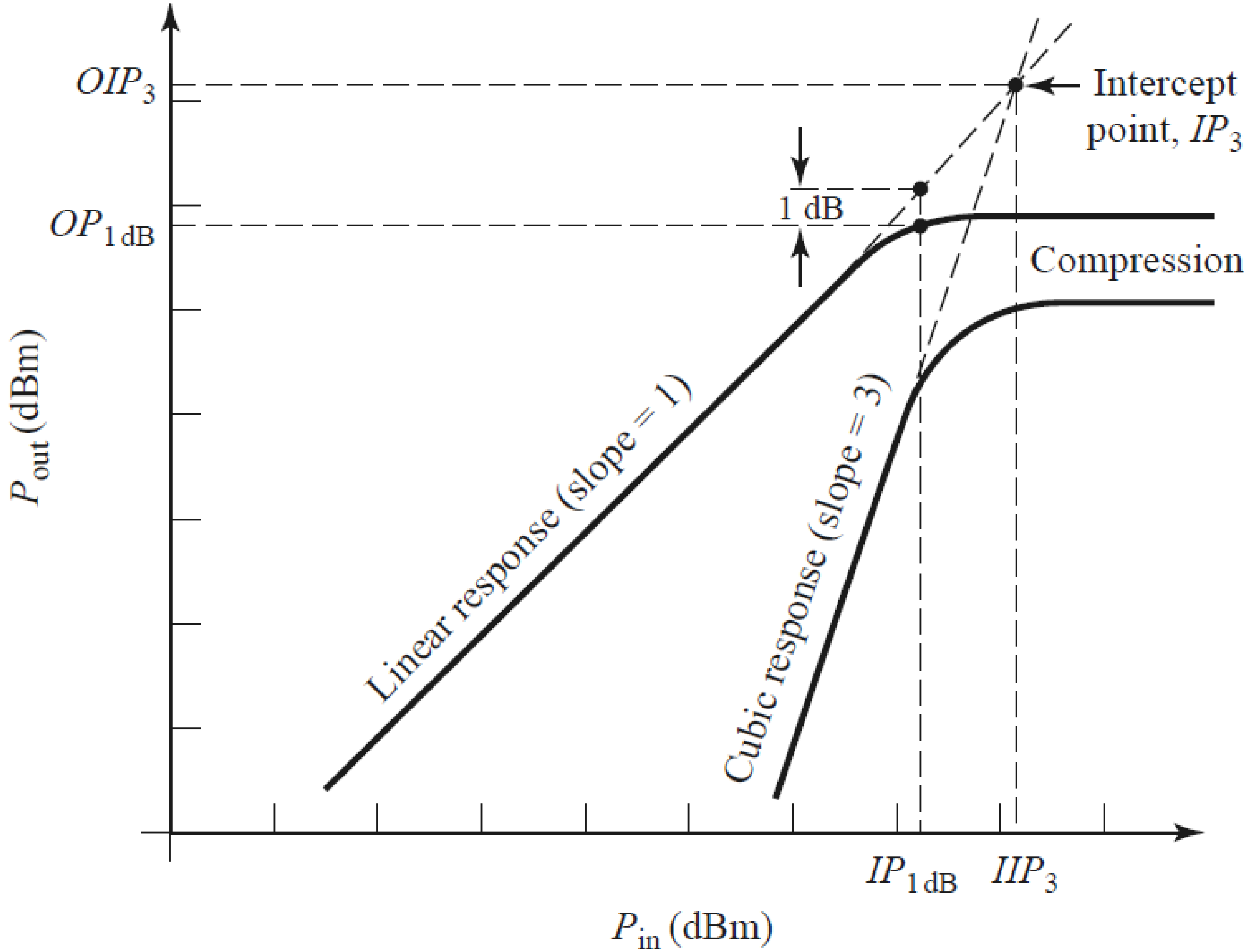


Second order intercept point: IP2



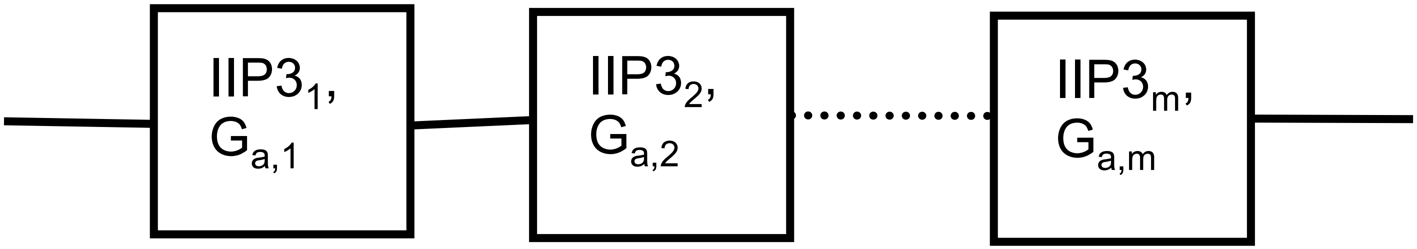
IIP2: input power where wanted power = second order power (extrapolated point).

Third order intercept point



IIP3: input power where wanted power = the third order power (extrapolated point).

Cascaded IIP3 formula



System with cascaded sub-systems with input IIP3 $IIP3_m$ and available gain $G_{a,m}$

$$\frac{1}{IIP3_{total}} = \frac{1}{IIP3_1} + \frac{G_{a,1}}{IIP3_2} + \ldots + \frac{G_{a,1}G_{a,2}\ldots G_{a,(m-1)}}{IIP3_m}$$

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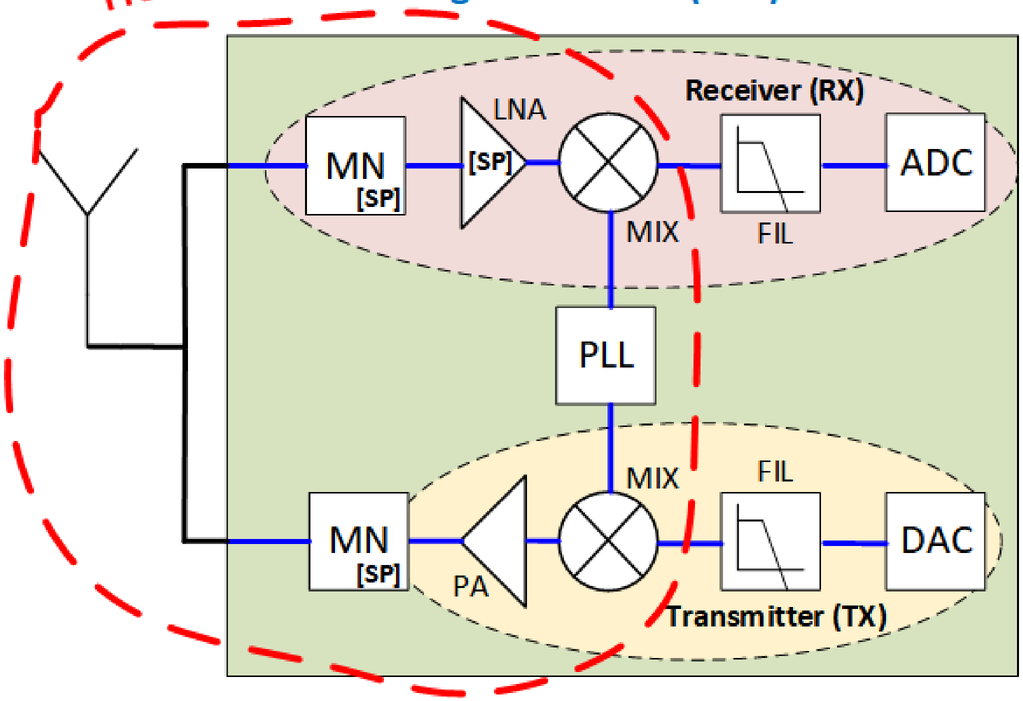
Transceiver functions

Analog Transceiver (TRX) - Radio



Analog transceiver functions

No	Functions	Building block	Symbol
1	Digitization	ADC	IN – ADC – OUT
2	Amplification	Amplifier	IN – ▷ – OUT
3	Filtering	Filter	IN – [filter] – OUT
4	Frequency conversion	Mixer	IN – ⊗ – OUT, LO

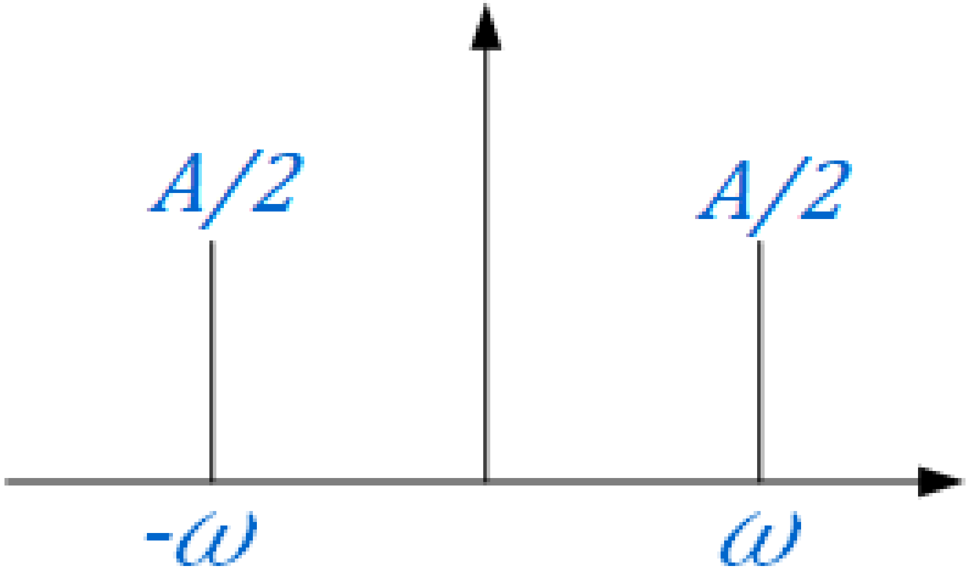
Spectra of cosine wave

- Time domain

$$x(t) = A\cos(\omega t)$$

$$x(t) = \frac{A}{2}(e^{j\omega t} + e^{-j\omega t})$$

- Frequency domain



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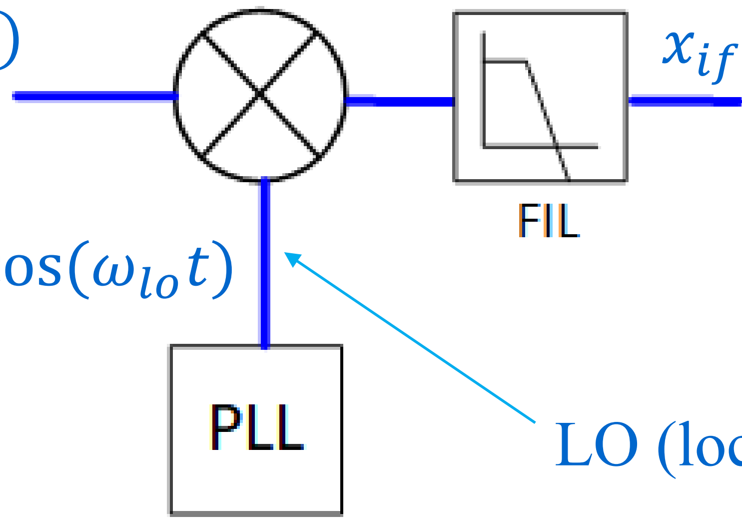
Mixing function in time domain – RX case

$x_{rf}(\mathrm{t}) = A_{rf}\cos(\omega_{rf}t)$

$x_{if}(\mathrm{t}) = A_{if}\cos(\omega_{if}t)$



$x_{lo}(\mathrm{t}) = A_{lo}\cos(\omega_{lo}t)$

LO (local oscillator) signal

$$x_{if}(\mathrm{t}) = A_{rf}\cos(\omega_{rf}t)\,A_{lo}\cos(\omega_{lo}t)$$

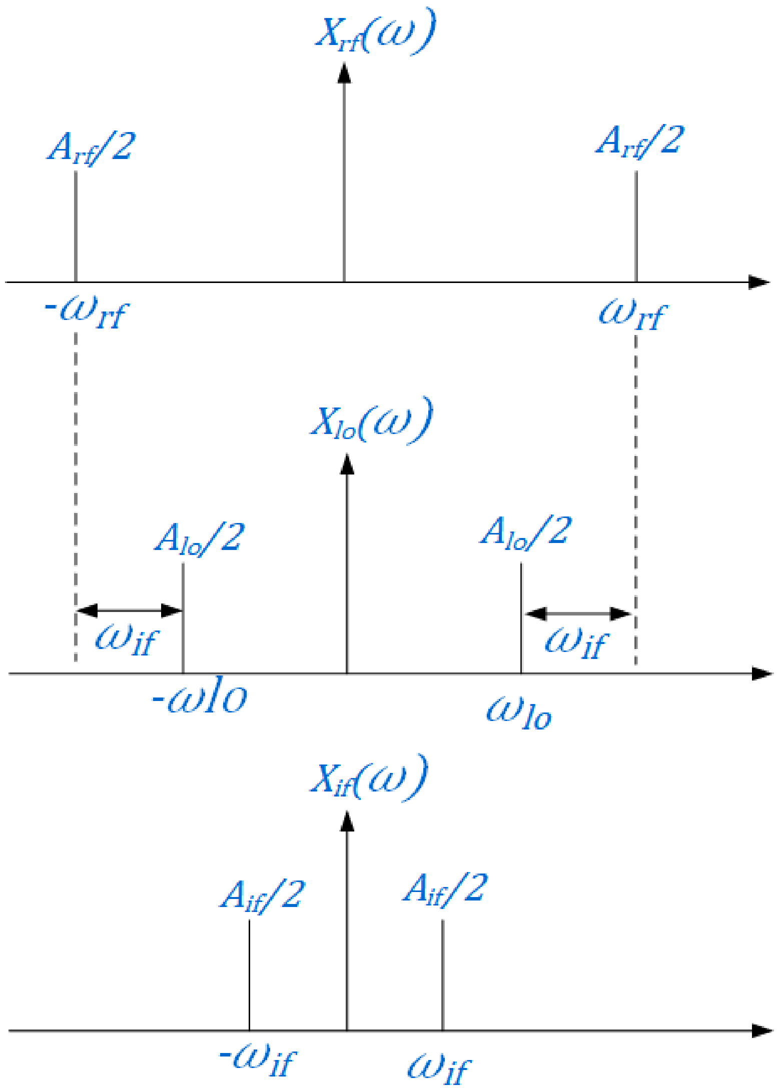
$$x_{if}(\mathrm{t}) = \frac{1}{2}A_{rf}\,A_{lo}\left(\cancel{\cos\left((\omega_{rf}+\omega_{lo})t\right)} + \cos\left((\omega_{rf}-\omega_{lo})t\right)\right)$$

$$\boxed{A_{if} = \frac{1}{2}A_{rf}\,A_{lo}}$$

$$\boxed{\omega_{if} = \omega_{rf} - \omega_{lo}}$$

Due to low-pass filter

Mixing function in frequency domain – RX case



- **Time domain**

$$x_{if}(\mathrm{t}) = x_{rf}(t)\,x_{lo}(t)$$

multiplication

- **Frequency domain**

$$X_{if}(\omega) = X_{rf}(\omega) * X_{lo}(\omega)$$

convolution

Technische Universiteit **Eindhoven** University of Technology

Image problem – time domain (info only)

$$x_{rf}(t) = 2A_w \cos(\omega_w t) + 2A_i \cos(\omega_i t) \tag{2.7}$$

A_w and A_i are half of the amplitudes of the wanted and unwanted signal, respectively. The sinusoidal LO signal can be expressed as:

$$x_{lo}(t) = 2A_{lo} \cos(\omega_{lo} t) \tag{2.8}$$

The signal at the mixer output ($x(t)$) is obtained by multiplying the signals $x_{rf}(t)$ and $x_{lo}(t)$:

$$x(t) = x_{rf} \cdot x_{lo} \tag{2.9}$$

Substituting (2.7) and (2.8) into (2.9), $x(t)$ can be expressed as:

$$\begin{aligned} x(t) \quad = \quad & 2[A_w A_{lo} \cos((\omega_w + \omega_{lo})t) + A_w A_{lo} \cos((\omega_w - \omega_{lo})t)] + \\ & 2[(A_i A_{lo} \cos((\omega_i + \omega_{lo})t) + A_i A_{lo} \cos((\omega_i - \omega_{lo})t)] \end{aligned} \tag{2.10}$$

The high frequency components that are located at the frequencies $\omega_w + \omega_{lo}$ and $\omega_i + \omega_{lo}$ have to be filtered out. After the filtering, the down-converted signal becomes:

$$x_{if}(t) = 2A_{wd} \cos((\omega_w - \omega_{lo})t) + 2A_{id} \cos((\omega_i - \omega_{lo})t) \tag{2.11}$$

A_{wd} ($A_{wd} = A_w A_{lo}$) and A_{id} ($A_{id} = A_i A_{lo}$) are half of the amplitudes of the down-converted wanted and unwanted signals, respectively. In the case that

$$\omega_i \leq \omega_{lo} \leq \omega_w \tag{2.12}$$

and

$$\omega_{lo} - \omega_i = \omega_w - \omega_{lo} \tag{2.13}$$

the unwanted signal is down-converted to the same IF as the wanted signal.

Image problem – frequency domain (info only)

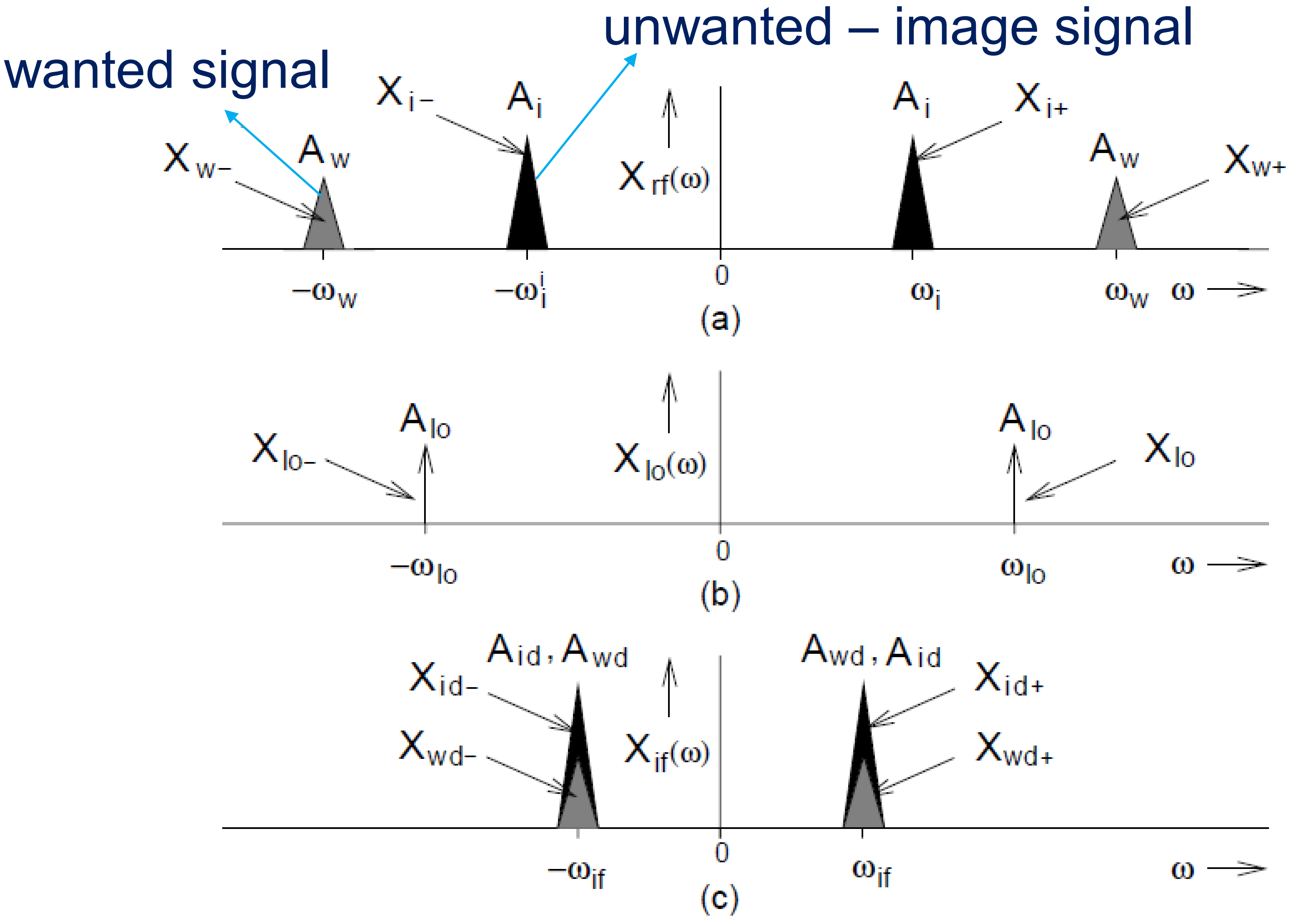
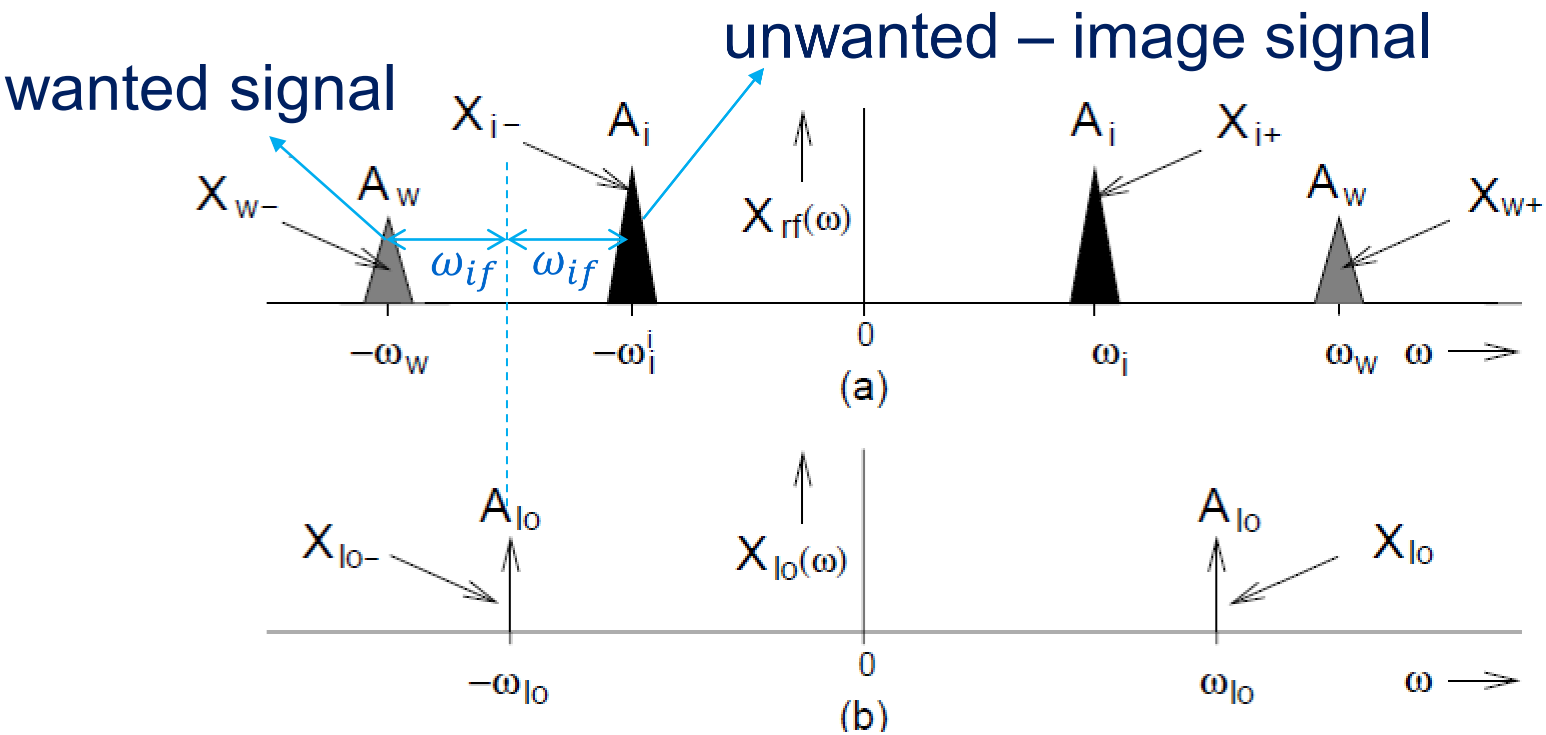
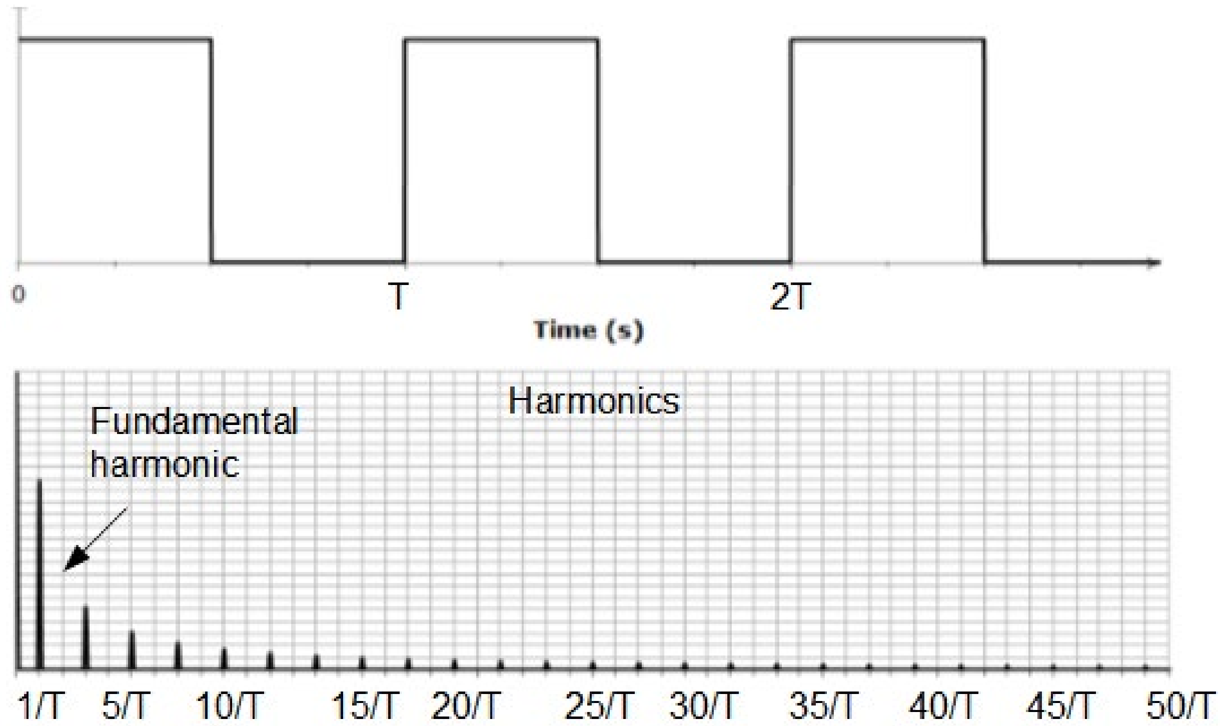


Image problem – summary (info only)



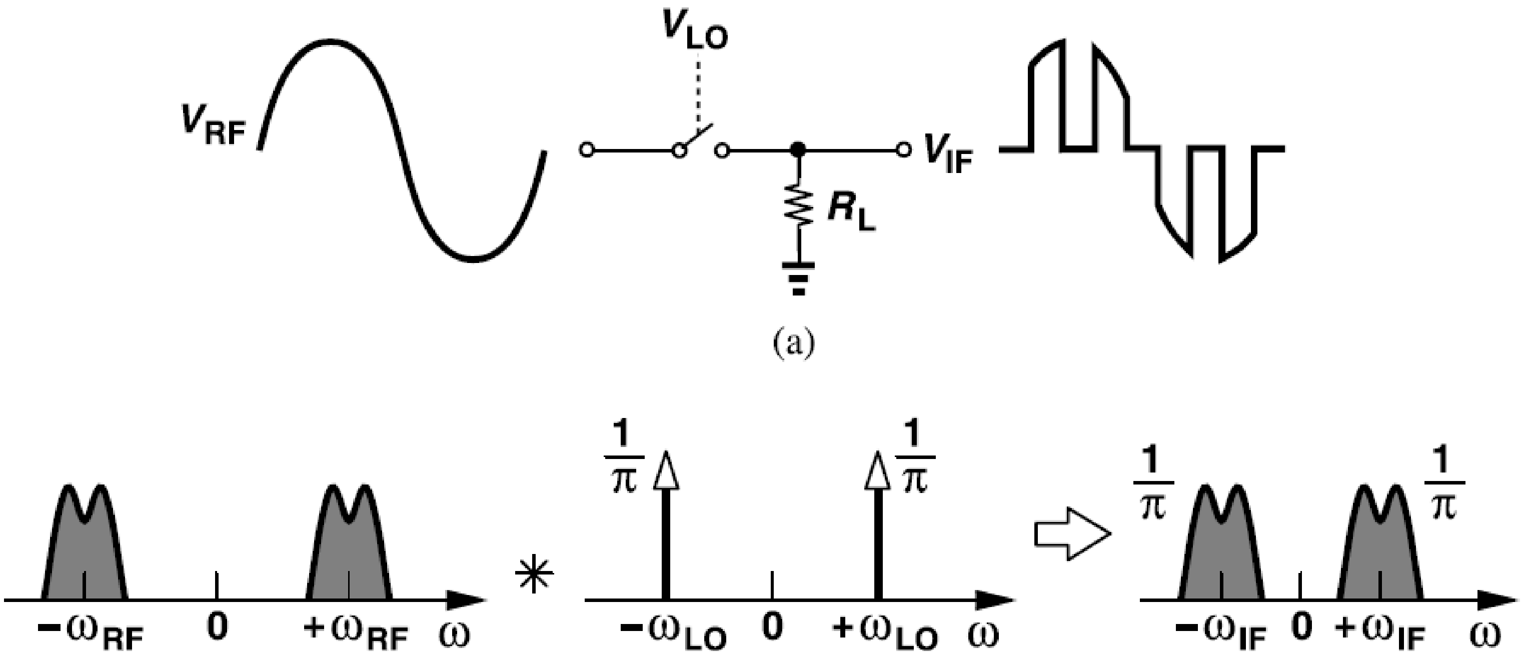
- Image signal is unwanted signal
- Image signal is located at frequency $\omega_{lo} - \omega_{if}$
- Image signal is down-converted to the same ω_{if} as wanted signal
- Image signal degrades SNR

Spectrum of square wave (info only)



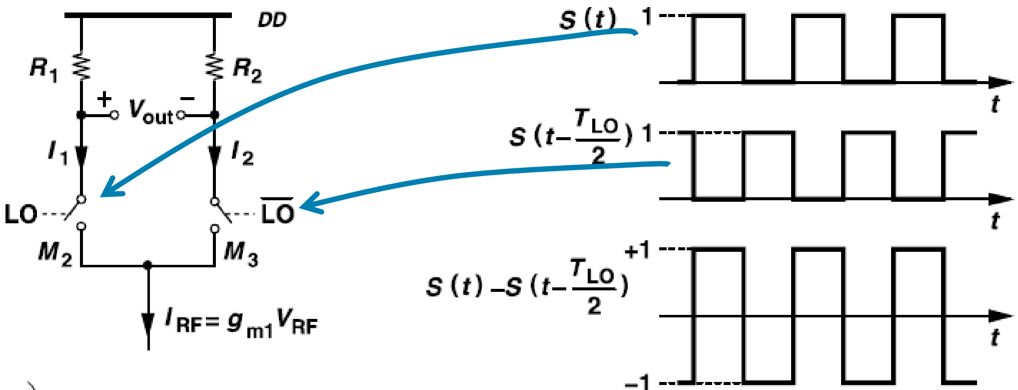
- Fundamental harmonic can be used for mixing as LO

Implementation of mixing by switching (info only)



- Mixing can be implemented by real multiplication, but using switching is the most common way how mixing is implemented in practice

Gilbert cell mixer – operating principle (info only)



$I_1 = I_{RF} \cdot S(t)$

$I_2 = I_{RF} \cdot S\left(t - \frac{T_{LO}}{2}\right).$

(a) (b)

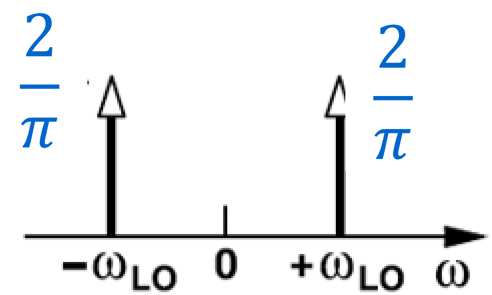


Figure 6.44 *(a) Equivalent circuit of active mixer, (b) switching waveforms.*

Since $V_{out} = V_{DD} - I_1R_1 - (V_{DD} - I_2R_2)$, we have for $R_1 = R_2 = R_D$,

$$V_{out}(t) = I_{RF}R_D\left[S\left(t - \frac{T_{LO}}{2}\right) - S(t)\right]. \tag{6.57}$$

From Fig. 6.44(b), we recognize that the switching operation in Eq. (6.57) is equivalent to multiplying I_{RF} by a square wave toggling between -1 and $+1$. Such a waveform exhibits a fundamental amplitude equal to $4/\pi$,[4] yielding an output given by

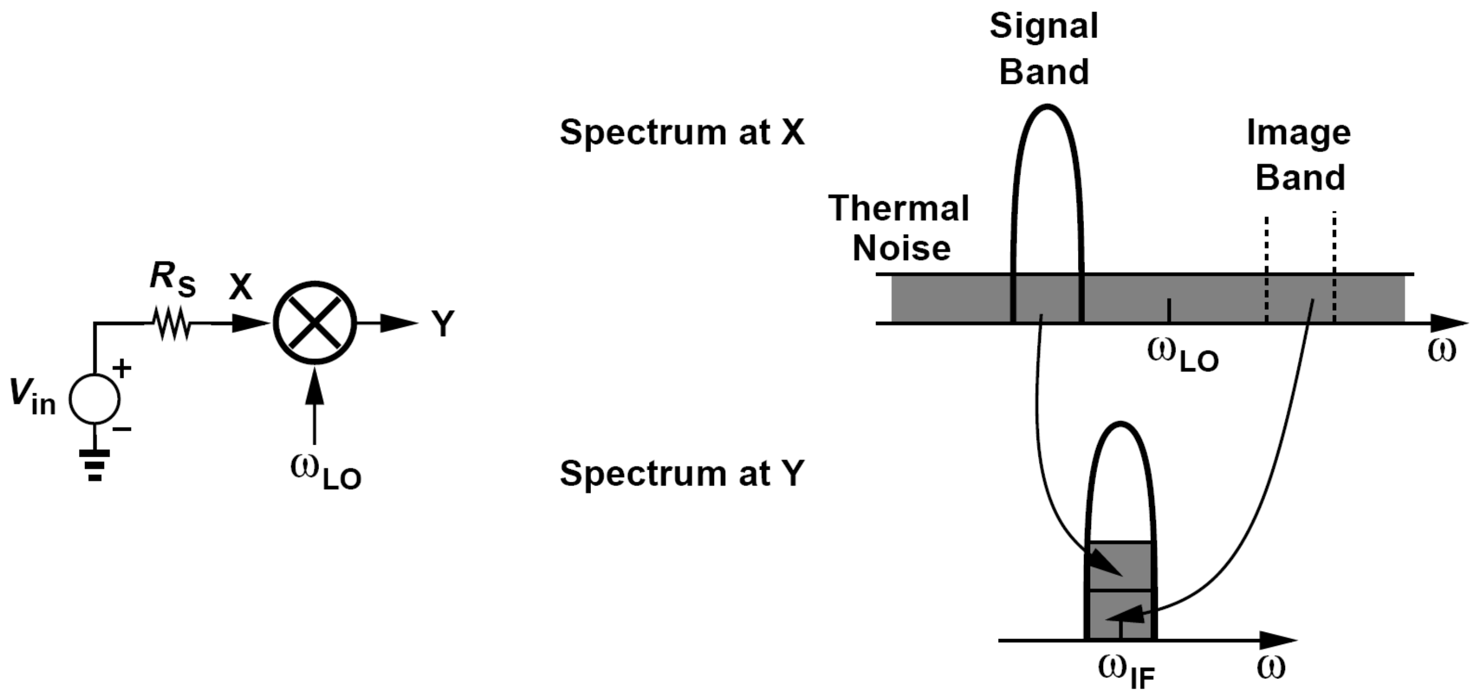
$$V_{out}(t) = I_{RF}(t)R_D \cdot \frac{4}{\pi}\cos\omega_{LO}t + \cdots. \tag{6.58}$$

If $I_{RF}(t) = g_{m1}V_{RF}\cos\omega_{RF}t$, then the IF component at $\omega_{RF} - \omega_{LO}$ is equal to

Mixer gain

$$V_{IF}(t) = \frac{2}{\pi}g_{m1}R_D V_{RF}\cos(\omega_{RF} - \omega_{LO})t. \tag{6.59}$$

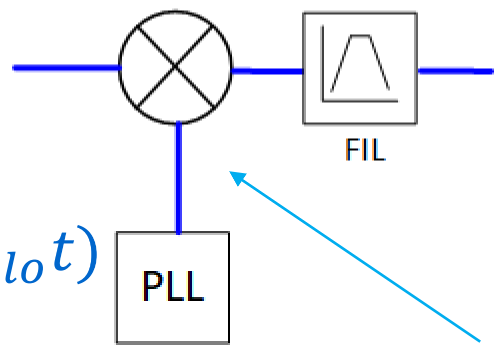
Mixer noise figure (info only)



- The mixer exhibits a flat frequency response at its input from the image band to the signal band.
- The noise figure of a noiseless mixer is 3 dB. This quantity is called the "single-sideband" (SSB) noise.
- In practice, taking into account mixer noise, noise figure is much higher, around 10dB

Mixing function in time domain – TX case

$x_{if}(\mathrm{t}) = A_{if}\cos(\omega_{if} t)$



$x_{rf}(\mathrm{t}) = A_{rf}\cos(\omega_{rf} t)$

$x_{lo}(\mathrm{t}) = A_{lo}\cos(\omega_{lo} t)$

LO (local oscillator) signal

$$x_{rf}(\mathrm{t}) = A_{if}\cos(\omega_{rf} t)\, A_{lo}\cos(\omega_{lo} t)$$

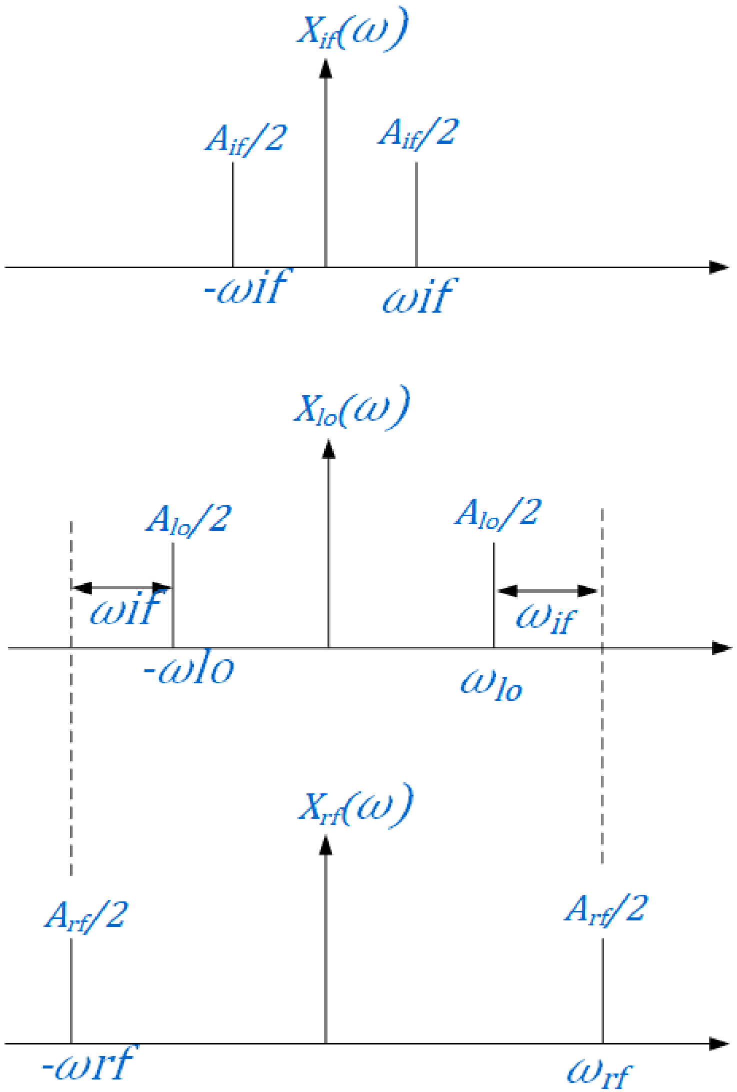
$$x_{rf}(\mathrm{t}) = \frac{1}{2} A_{if}\, A_{lo}\left(\cos\Big((\omega_{if} + \omega_{lo})t\Big) + \cancel{\cos\Big((\omega_{if} - \omega_{lo})t\Big)}\right)$$

$$\boxed{A_{rf} = \frac{1}{2} A_{if}\, A_{lo}}$$

$$\boxed{\omega_{rf} = \omega_{if} + \omega_{lo}}$$

Due to band-pass filter

Mixing function in frequency domain – TX case



- **Time domain**

$$x_{rf}(\mathrm{t}) = x_{if}(t)\,x_{lo}(t)$$

multiplication

- **Frequency domain**

$$X_{rf}(\omega) = X_{if}(\omega) * X_{lo}(\omega)$$

convolution

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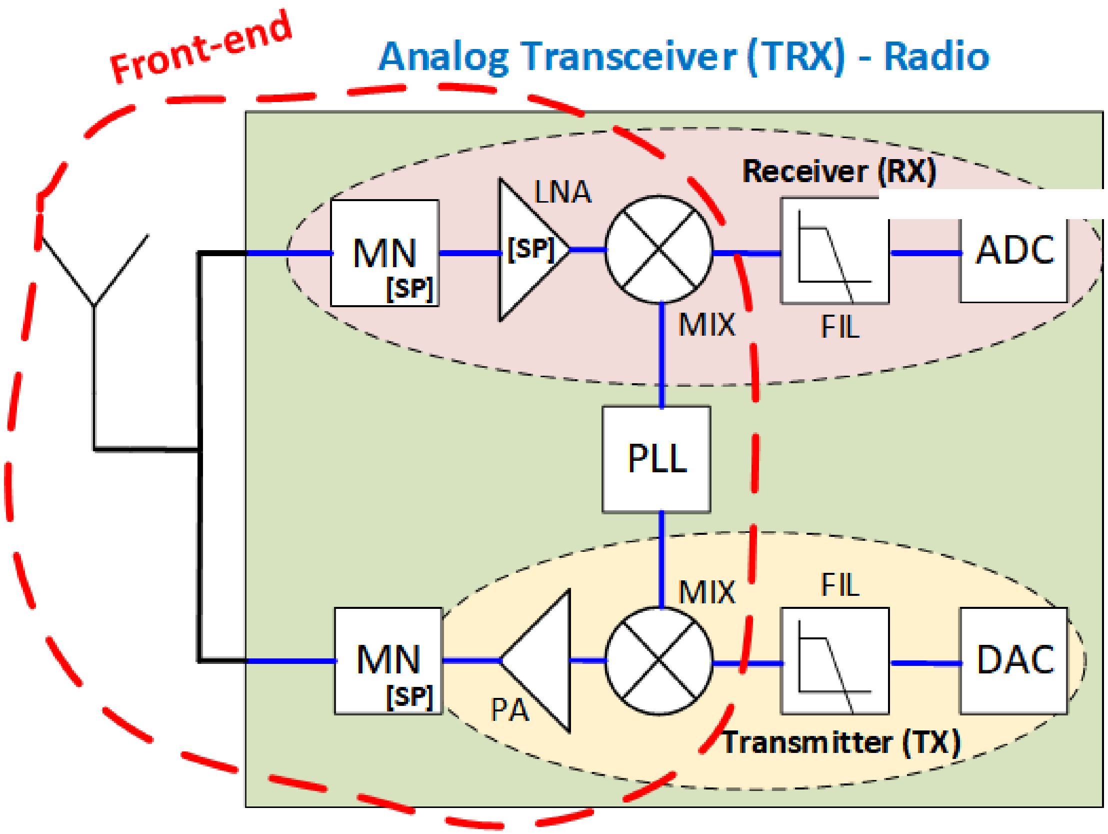
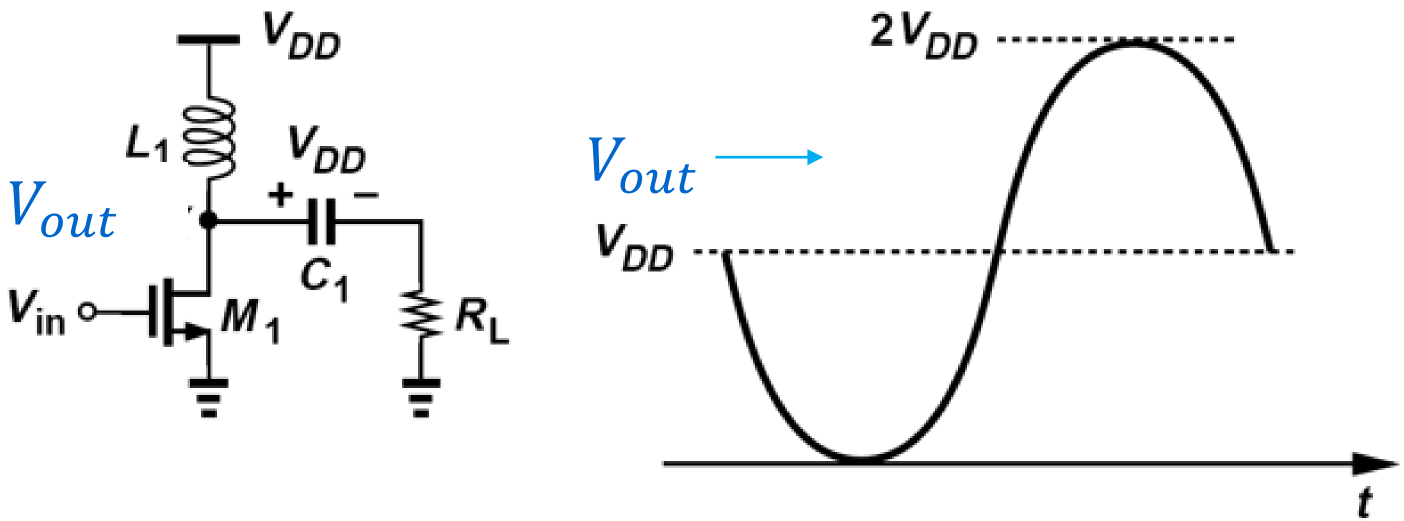
- **Basics of power amplifiers**

TX – output power requirements



- Antenna is a load for a PA
- PA is expected to deliver power to the antenna

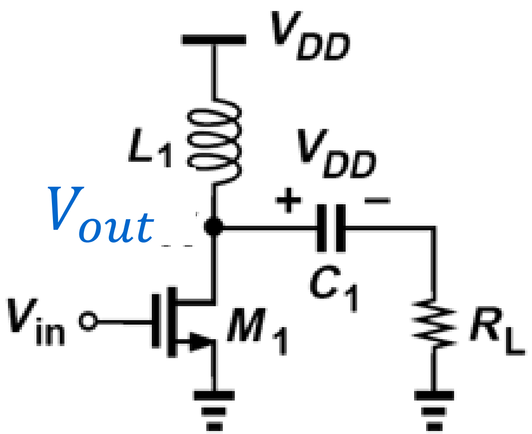
Power generation - limitation

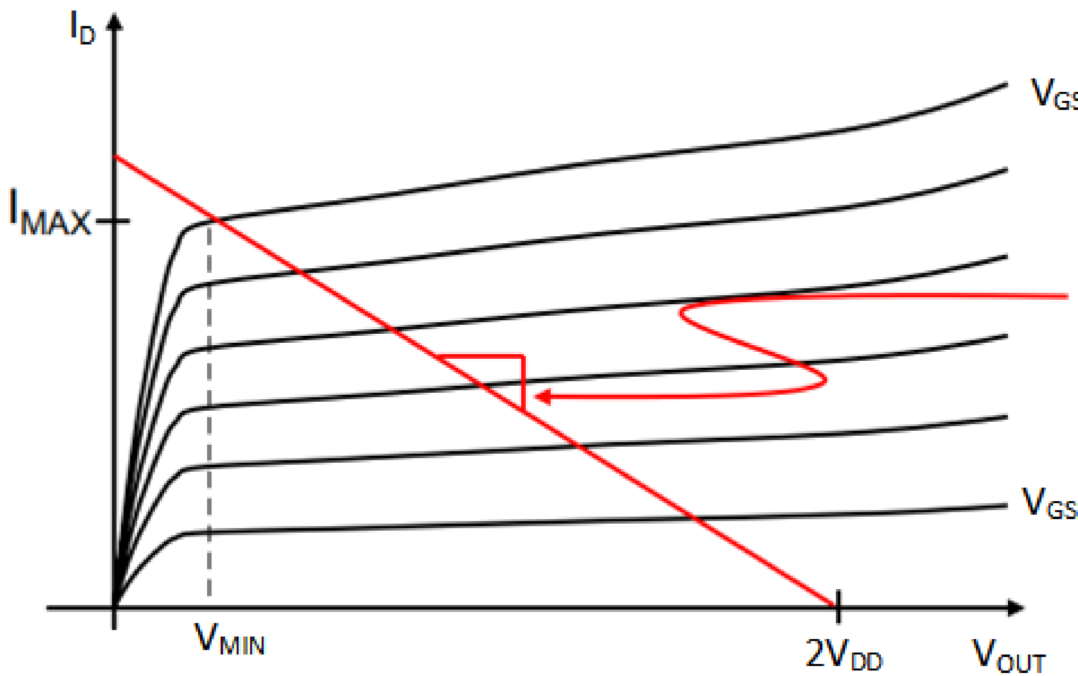


- Output power $P_{out@R_L} = \dfrac{V_{out}^2}{R_L}$

- Output power limited by load R_L and supply V_{DD}
- Supply V_{DD} is limited by technology
- The only way to improve output power is selecting right R_L

Optimum load for power amplifier (info only)

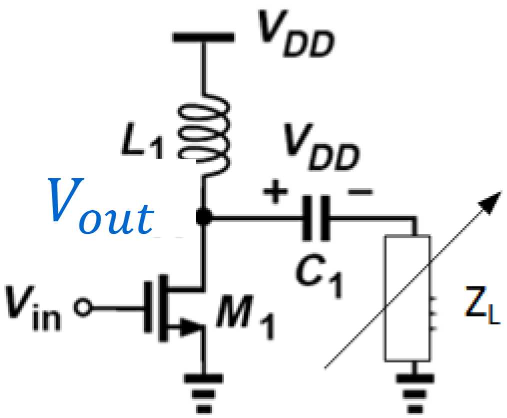


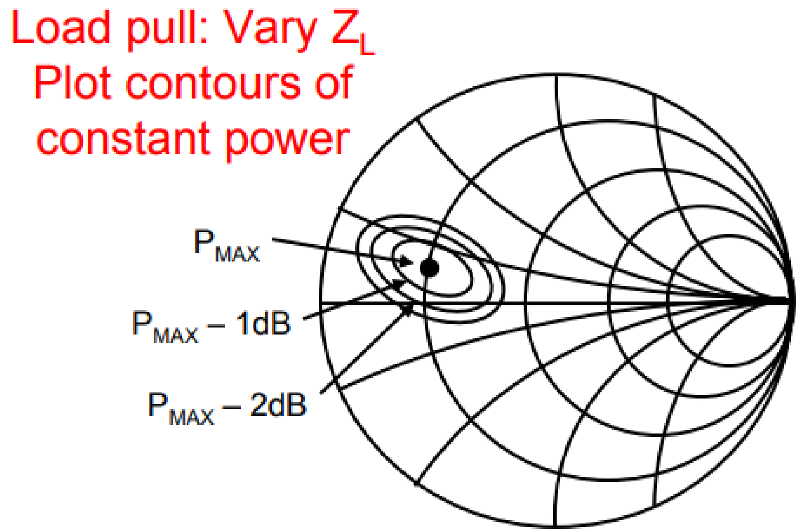


- Optimum load $R_L = \dfrac{2V_{DD} - V_{MIN}}{I_{MAX}}$

- Load-pull simulations provide R_L

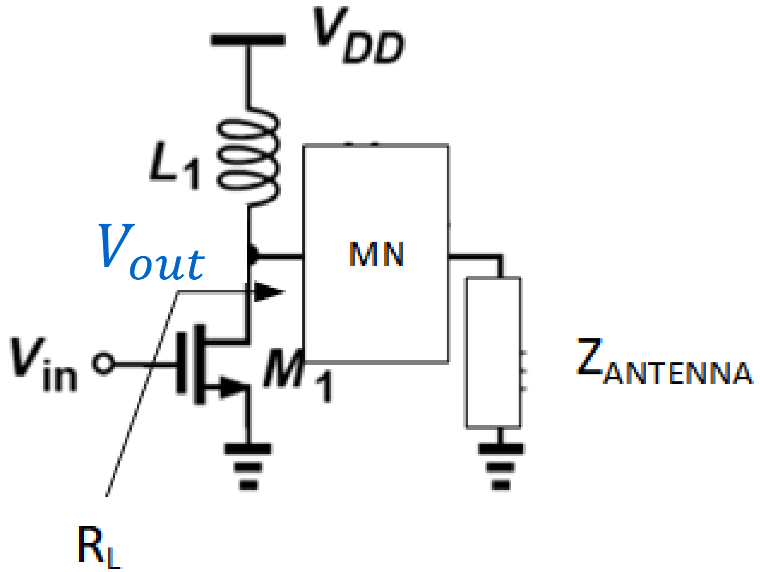
Load-pull simulations





- Optimum load found by sweeping
- Load-pull simulations results in constant power contours

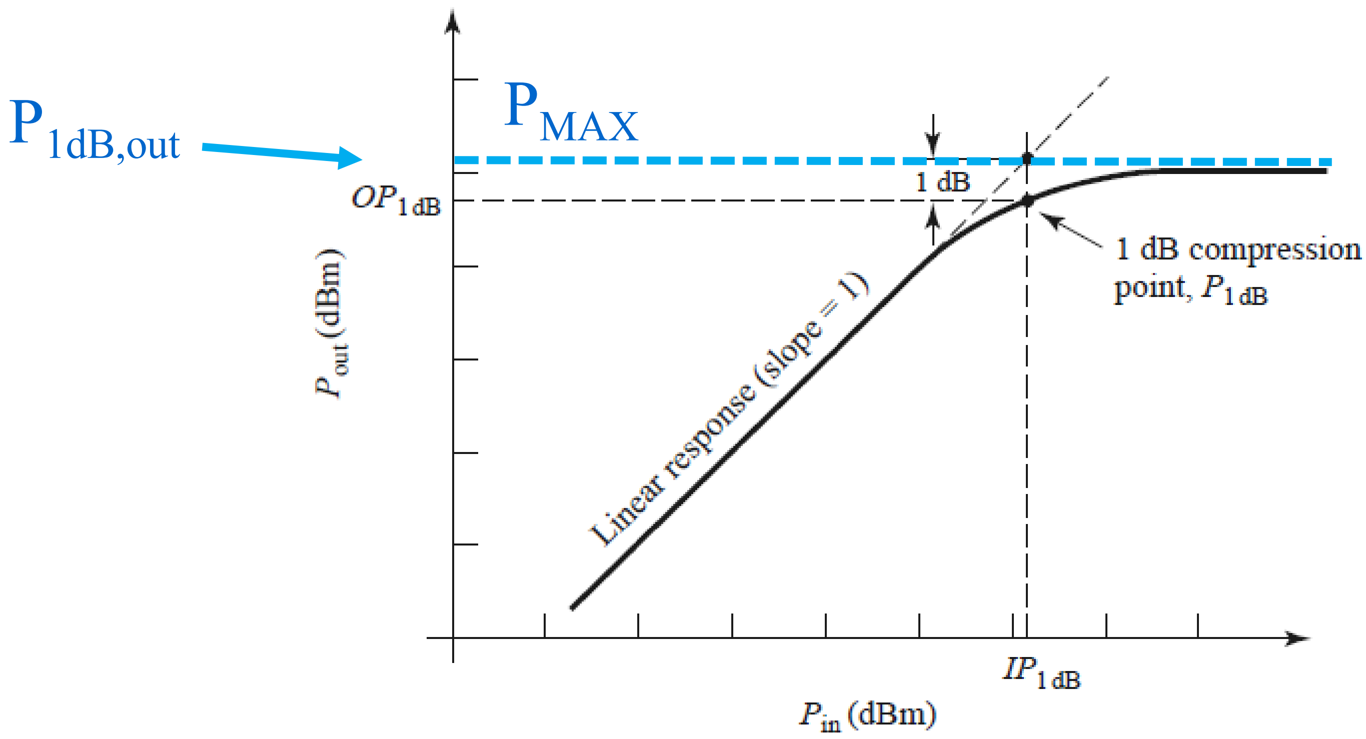
Matching network for PA



- Matching network transform antenna impedance to optimum load

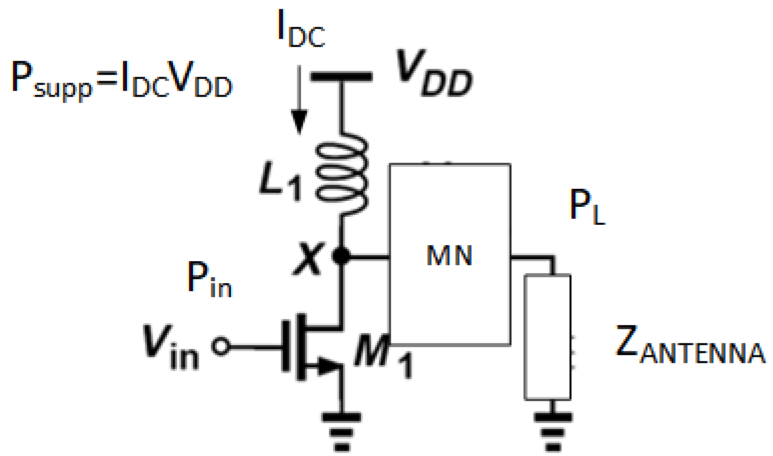
PA performance parameters: $P_{1dB,out}$, P_{MAX}

- Output 1-dB compression point: $P_{1dB,out}$



- Maximum output power: P_{MAX}

PA performance parameters: efficiency



The "drain efficiency" (for FET implementations) or "collector efficiency" (for bipolar implementations) is defined as:

$$\eta = \frac{P_L}{P_{supp}}$$

where P_L denotes the average power delivered to the load and P_{supp} the average power drawn from the supply voltage.

"Power-added efficiency", PAE, defined as

$$\text{PAE} = \frac{P_L - P_{in}}{P_{supp}}$$

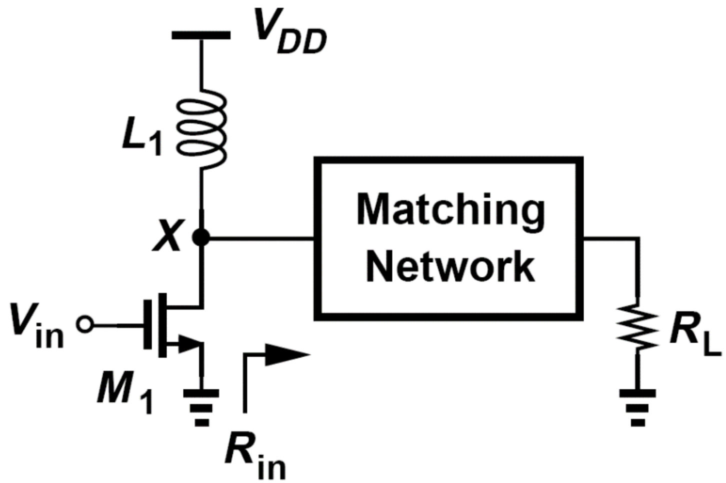
where P_{in} is the average input power

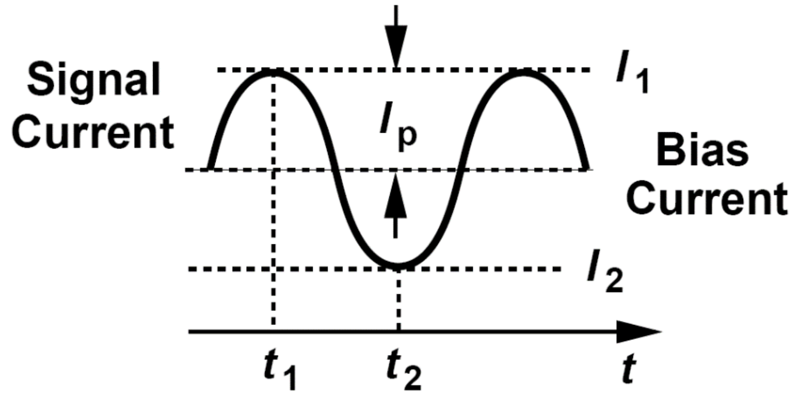
PA classes

- Based on operating point PAs can be divided into:
  - Class A
  - Class B
  - Class C
  - Class D
  - Class F
  - Class E

Out of scope for this course

PA operation in class A (info only)





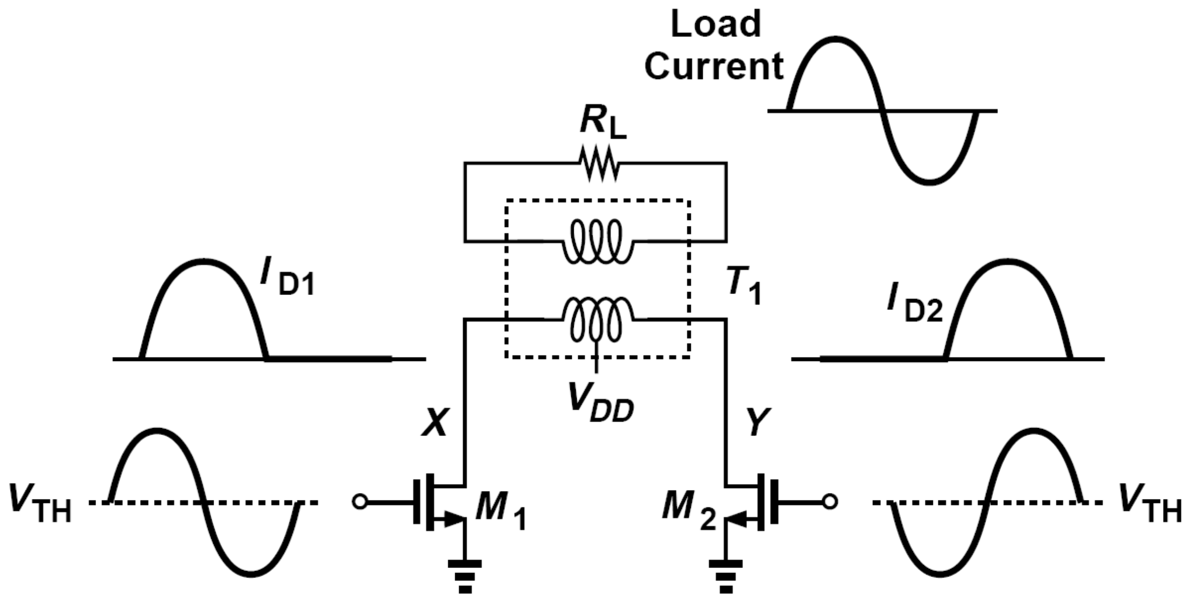
- Class A amplifiers are defined as circuits in which the transistor(s) remain on and operate linearly across the full input and output range.
- If linearity is required, then class A operation is necessary.

The maximum drain efficiency of class A amplifiers:

$$\eta = \frac{V_{DD}^2/(2R_{in})}{V_{DD}^2/R_{in}} = 50\%.$$

PA operation in class B (info only)

- Conduction Angle is defined as the percentage of the signal period during which the transistor remain on multiplied by 360 °



- The traditional class B PA employs two parallel stages each of which conducts for only 180° , thereby achieving a higher efficiency than the class A counterpart.